RECENT FLIGHT TEST RESULTS USING AN ELECTRONIC DISPLAY FORMAT ON THE NASA B-737

Samuel A. Morello
Aero-Space Technologist
Flight Research Division
NASA Langley Research Center
Hampton, Virginia 23665

SUMMARY

This paper presents the results of a flight evaluation of two electronic display formats for the approach-to-landing under instrument conditions. The evaluation was conducted for a baseline electronic display format and for the same format with runway symbology and track information added. The evaluation was conducted during 3°, manual, straight-in approaches with and without initial localizer offsets. Flight-path tracking performance data and pilot subjective comments were examined with regard to pilot's ability to capture and maintain localizer and glideslope using both display formats.

The results of the flight tests agree with earlier simulation results and show that the addition of a perspective runway symbol with an extended centerline and relative track information to a baseline electronic display format improved both lateral and vertical flight-path tracking. Pilot comments indicated that the mental workload required to assess the approach situation was reduced as a result of integrating perspective runway with extended centerline along with relative track information into the vertical situation display. The limited flight test results also show that the flight-path performance with the integrated situation display format meets Category II Flight-Director performance criteria.

Flight-path tracking results of close-in, curved approaches using the integrated vertical situation display format and predictive information on the horizontal situation display will also be presented.

SYMBOLS

ATTSYNC	Attitude Synchronization
$\dot{h}$	Complementary filtered altitude rate
k	Constant
LAT	Latitude
LONG	Longitude
PCOD	Pitch Control Out of Detent
Pitch PMC	Pitch Panel Mounted Controller
RCE	Roll Computer Enable
RCOD	Roll Control Out of Detent
Roll PMC	Roll Panel Mounted Controller
s	Laplace transform
t	Time
V_E	East velocity
V_N	North velocity
$\ddot{y}$	Crosstrack acceleration as measured in an inertial axis
β	Angle of glide-path deviation
δ_{ac}	Aileron command
δ_{ec}	Elevator command
η	Angle of lateral-path deviation
γ	Flight path angle as measured in an inertial axis
γ_c	Commanded flight path angle
θ	Aircraft pitch angle
$\dot{\theta}$	Aircraft pitch rate

ϕ	Aircraft roll angle
$\dot{\phi}$	Aircraft roll rate
	Aircraft yaw angle

INTRODUCTION

One of the objectives of the NASA Terminal Configured Vehicle (TCV) Program is the research and development of electronic display concepts that will improve pilot instrumentation for the approach-to-landing task in low visibility. Present-day electromechanical instrumentation has been very beneficial in achieving low visibility landings on long, straight-in final approach paths. This instrumentation, however, is considered to be inadequate for the low visibility approach to landing on close-in, curved, approach paths that may be required in the future. As discussed in reference 1, the increased number of parameters that the flight crew may be required to control or monitor will also demand that information be processed and displayed in an integrated, [illegible] to convey a naturally assimilated mental picture of a complex situation. The flight experiment [illegible] TCV program incorporate electronic displays which offer capabilities not currently found in electromechanical display systems. Considering this increased capability, a specific guideline or philosophy within the display information research is to investigate means of presenting improved situation information to the pilot. A display format is desired that will aid the pilot in maintaining a mental picture of his current situation relative to the runway and extended centerline during the approach to landing under instrument conditions. To achieve this objective, an integrated situation display format was developed that was aimed at presenting, in a single display, the necessary information for the approach-to-landing task, whether flown manually or automatically. This display format was evaluated in a piloted-simulation study where horizontal situation information, in the form of perspective runway and relative track symbology, was integrated into an existing vertical situation display format.

This paper presents the results of flight tests aimed at evaluating a baseline electronic display format and an integrated electronic display format in the actual flight environment. Piloted simulation results, reported in reference 2 and presented in this report, are compared with the flight-test results. The flight tests were conducted in the TCV B-737 utilizing an aft flight deck (AFD) and a velocity vector control mode. Results of straight-in, 3^{o} approaches with and without initial localizer offsets at 3 nautical miles from the runway threshold are discussed. Flight-path accuracy data and pilot comments are presented and compared with Flight-Director performance criteria. Flight-path tracking results and pilot comments are also presented in the Results and Discussion section for close-in, curved approaches with 1.5-and 1.0-nautical mile, straight-in final approach segments.

TEST AIRPLANE AND EXPERIMENTAL SYSTEMS

The flight-test facility used in the TCV program is a modified Boeing 737-100 twin-engine jet transport shown in cutaway form in figure 1. Shown is the arrangement of palletized research installations aboard the test aircraft. Major components consist of a standard forward cockpit, an aft flight deck (AFD), navigation and guidance pallets, flight control computers, and a data acquisition system.

The two-man aft flight deck, shown in figure 2, consists of primary flight controls including conventional rudder pedals and panel-mounted controllers (PMC) for pitch and roll control. This cockpit has a fly-by-wire interface with the basic aircraft systems for both manual (semi-automatic) and fully automatic control of the airplane. With the exception of gear and speed brake actuation, direct electrical tie-in to flaps and throttles is provided to the research pilots. For safety monitoring purposes, control surface inputs are reproduced in the forward cockpit.

Flight control functions are managed through the use of the Advanced Guidance and Control System (AGCS) provided in the aft flight deck. The AGCS concept is shown in figure 3. The digital [illegible] control computer which is triple redundant with a variable-increment capability provides the [illegible] computational function for the flight control system. The fail-operational computer has programmable memory in which controls laws are solved in real time. The system interfaces the pilot and crew with the normal flight functions of navigation, guidance, display, and automatic control. Mode selection is available by using the AGCS mode select panel. The navigation-guidance computer, sensors, and three incremental flight control computers are the major elements of this system.

Crew communication with the navigational computer is made through the Navigation Control/Display Unit (NCDU) which has a keyboard for data input and a cathode-ray tube for data display on which paths can be synthesized during flight. The primary piloting displays of the AGCS are the Electronic Attitude Director Indicator (EADI) and the Electronic Horizontal Situation Indicator (EHSI). Additional details of the navigation, guidance and display systems are shown in block diagram in figure 4.

Depending on the mode selected, the aft flight deck pilot has available an attitude or velocity vector control mode. Only the velocity vector control mode was used in this study. Figures 5 and 6 are block diagrams of the pitch and roll control modes. Basically, these control modes provide the pilot with augmented control of the aircraft laterally and longitudinally. When pitch PMC is applied above the detent level, airplane pitch rate is commanded proportional to controller deflection. When the pilot releases his input and the controllers are recentered, airplane flight-path angle is maintained.

In the roll axis, the velocity vector control mode is designed to hold the airplane's attitude constant after roll PMC if bank angle is greater than 5^0. If the bank angle at controller release is less than 5^0, the control system maintains the airplane's present ground track by modulating bank angle.

Data were recorded onboard the aircraft on a wide-band magnetic tape recorder at 40 samples per second. Typical recorded data consisted of three-axis body angular position and rate information as well as pilot control inputs. Ground-based tracking data were obtained from a phototheodolite facility. The facility is a four-station optical instrumentation complex which provides accurate space-position-time location of a target within 15 nautical miles of the airport.

FLIGHT EXPERIMENT

The primary objective of the flight experiment was to evaluate the effect of adding horizontal situation information, consisting of a perspective runway symbol with extended centerline and a relative track-angle indicator, to a previously established vertical situation display format. (See Ref. 2.)

Figure 7 presents the information that can be presented on the EADI. The perspective runway symbology, drawn on a 30^0 by 40^0 field of view, includes the basic outline of the runway, a centerline drawn one nautical mile before the runway threshold to the horizon. The magnification factor was between 0.3 and 0.5, depending on pilot seat position. The runway symbol represents a runway 3,048 meters (10,000 feet) in length and 45.72 meters (150 feet) in width. Four equally spaced lines were drawn perpendicular to the centerline of the runway at 304.8 meters (1,000 feet) intervals. Two lines parallel to the centerline of the runway were drawn on the runway dividing it into equal quarters. The mathematics of drawing the runway symbology are detailed in reference 2.

The relative track angle indicator pictorially shows the inertially referenced track angle of the airplane relative to the runway heading. Relative track angle information was indicated by a tab that moved along the horizon line of the EADI. A track scale with 10^0 increments referenced to the runway heading was drawn on the horizon line of the EADI. The pilot using the track pointer and scale could determine the magnitude of the relative track angle of the airplane to the runway.

The evaluation process was both qualitative and quantitative. Pilot opinion concerning the ability to understand and use the displayed information as well as tracking performance data were analyzed for the final approach-to-landing task. Onboard data instrumentation and ground-based tracking theodolite data were recorded and analyzed.

DISPLAY FORMATS TESTED

The navigation, guidance, and display subsystems have been integrated into a single system, as can be seen in figure 4. The system utilized digital computation, information processing, and transmission techniques, together with cathode-ray tube (CRT) displays. The EADI was the primary display used by the evaluation pilots and measures 12.70- by 17.78-centimeters (5- by 7-inches).

Two display formats were presented on the EADI for evaluation purposes. Figure 8 is a drawing of the baseline format on the EADI, which consists primarily of the airplane's attitudes, flight-path information, and flight-path deviations. Included in the baseline display format is the EHSI, also shown in this figure. Presented on the EHSI are the airplane symbol for present position information, a 30-second curved trend vector (predicted position information 30 seconds ahead), runway and extended centerline, and digital readout and scale of present track angle.

Figure 9 is a drawing of the integrated situation information format and basically contains the addition of the perspective runway symbology and relative track information.

The flight tests reported here were flown using the Time Referenced Scanning Beam Microwave Landing System (MLS) located at the National Aviation Facilities Experimental Center. The airplane's basic navigation, guidance, and display system was modified, as shown in figure 10, for compatibility with the MLS. The MLS receiver processor provided raw decoded MLS elevation and azimuth angular information and filtered range data to the MLS guidance signal processor. The MLS guidance signal processor utilized the MLS information and data from the aircraft sensors to prefilter the raw data, perform coordinate transformation, and process the transformed data into position, velocity, and acceleration estimates. These data were then sent to the navigation and guidance computer for display information computation. The MLS processed signals used for display computations are shown in figure 11. Position (LAT. LONG), velocity (V_N, V_E, $\dot{h}$), acceleration ($\ddot{y}$), and path error (η,β) signals are utilized to compute displayed information for both the EADI and EHSI. Airplane attitudes, from onboard sensors, were also used in the perspective runway computation. Detailed information concerning the MLS receiver and guidance signal processors are presented in reference 3.

EXPERIMENTAL TASK

The experimental task required the pilot to track a straight-in MLS path to the runway threshold. The MLS path was a 3^0 ($\pm1^0$) glideslope that terminated on the runway 304.8 meters (1,000 feet) past the runway threshold. The localizer course was $\pm2.5^0$ wide and emanated from a point 2,605.8 meters (8,547 feet) past the runway threshold.

A localizer offset approach task was used to evaluate the benefits of the integrated display information for correcting relatively large lateral path errors. A planview of the 3-nautical mile, straight-in approach, with an initial segment consisting of a 130° turn on a 3° descent, is illustrated in figure 12. Guidance in the form of a dashed curved path was presented on the EHSI so that an initial localizer offset of approximately 0.1 nautical mile was obtained. The airplane was in the landing configuration (flaps 40°, gear down) prior to the turn and the autothrottle system was used to maintain the approach speed.

TEST SUBJECTS

Four NASA test pilots were used during the evaluation. Only three pilots, however, flew the localizer offset approach task. Two of the pilots were type-rated for the B-737, and the other two pilots had some flight experience in the B-737. All of the pilots had previous experience in the AFD simulator.

TEST PROCEDURE

The test procedure required the pilot to execute the 130° curved approach (without localizer offset) shown in figure 12 using both the EADI and EHSI display information. Once the turn had been completed (Waypoint FAF3M), the pilot was instructed to use primarily the display information in the EADI to track localizer centerline while maintaining the 3° glideslope.

Since the principle objective of the flight tests was to evaluate the use of presenting horizontal information in the EADI or vertical situation display, the second series of approaches concentrated on the localizer offset task. During these runs, the pilot was required to fly the localizer offset path (shown dashed in figure 12) to a point 0.1 nautical mile left of Waypoint FAF3M. At this point he was instructed to use primarily the displayed information on the EADI to capture and hold the localizer centerline, while tracking the glideslope.

The approaches, with and without the localizer offset, were flown using both the baseline and integrated display formats. The display format runs were randomized so that environmental conditions and pilot learning curve factors would be reduced. Although the pilot was told to use the EADI as the primary display, he was allowed to scan the EHSI and the basic flight instruments for information that might be missing in the EADI.

RESULTS AND DISCUSSION

Three-Nautical Mile Approach Tests

Localizer tracking performance was analyzed for both display formats to determine the benefits or disadvantages of integrating horizontal information into the vertical situation display. Figures 13 and 14 are plots of localizer deviation versus range from runway threshold for the approaches without localizer offset. Figure 13 presents the localizer tracking results of four approaches using the baseline situation display format as the primary display. As can be seen, the tracking is oscillatory in nature and the lateral deviations at times are larger than the runway width. Pilot comments indicated that pilot mental workload was high using the baseline format since the pilot had to scan the map display (EHSI) to obtain track information from the airplane symbol, trend vector symbology and the digital readout of track angle. The pilots felt that the lateral path guidance provided by the map display was not sufficient for a close in final approach even with the map scale set for greatest resolution, 0.394 nautical mile per centimeter (1 nautical mile per inch).

The localizer tracking performance using the integrated situation display format is presented in figure 14. This lateral tracking data show that the pilots could consistently complete the approach to landing with only small deviations from the runway centerline. Pilot comments indicated that the integrated display format on the EADI eliminated the need to scan the EHSI during the approach. The runway and relative track information enabled the pilot to better understand his position and trajectory relative to the extended runway centerline.

Figure 15 presents cross plots of glideslope and localizer deviations at 61- and 30.5-meter altitude windows. The data for the integrated display format show better localizer tracking and more consistent glideslope tracking. The integrated format reduces the amount of time the pilot needs to build the mental picture of his lateral position and predicted trajectory and enables him to spend more time on the glideslope task. It should be remembered that the displayed information of glideslope deviation is the same for both display formats, however, the runway symbology provides a reference point on the EADI for the flight-path angle symbols.

Figures 16 and 17 present the lateral tracking results of several approaches flown with the initial localizer offset (see Fig. 12) at 3 nautical miles from runway threshold. The lateral tracking results using the baseline display format are shown in figure 16 and illustrate the deficiency of this format to provide adequate close-in localizer path capture information. The tracking is oscillatory in nature with the final corrections back toward the extended centerline occurring very close to the threshold. Only one approach actually crosses the centerline, and none of the approaches ever achieves the proper track angle to the runway. The lack of good lead information and the fear of a large localizer overshoot brought about the centerline undershoots seen in this figure.

The lateral tracking results using the integrated situation display format are shown in figure 17. The data show that the pilots are able to make a precision capture of the localizer and maintain runway centerline tracking using only the integrated format presented on the EADI. After the flight-path corrections are made to capture the localizer, it can be seen that the track angle to the runway threshold is proper and stabilized for all the approaches.

Figure 18 presents cross plots of glideslope and localizer deviations at 61- and 30.5-meter altitude windows for the offset approaches. The data show that both glideslope and localizer errors are smaller for the integrated display format at both windows. Pilot comments indicated that the integrated format reduced the lateral task mental workload and allowed more time to be spent on the glideslope tracking task.

Figure 19 is a comparison of the 30.5-meter window data from the offset approaches with previous simulation data and with Category II Flight-Director criteria as stated in FAA Advisory Circular, AC 120-29. Figure 19(a) illustrates that the flight results for the integrated situation display format lie within the mean and standard deviation of the simulation results for the same format. The flight and simulation data for the baseline display format also show similar trends. The lateral bias in the simulation data is due to a steady left crosswind that was part of the experiment.

Figure 19(b) illustrates that the glideslope and localizer path performance with the integrated situation display format compares very favorably with Category II Flight-Director criteria. Three of the approaches made with the baseline display pass through the window criteria, but the pilots considered these approaches unsatisfactory because the airplane's attitudes and track were not stabilized.

Close-In Approach Tests

Following the approach tests with the 3-nautical mile final approach segments, both 1.5- and 1.0-nautical mile final approach path tasks were evaluated. The geometry of the close-in approach paths, including the 3^o descent and 130^o turn onto the final segment, was identical to the previous approaches. The only difference was the length of the final approach segment. The velocity vector control mode was used in this evaluation.

The EADI display format used during these tests was the integrated situation format that was used in the previous experiment. The format on the EHSI differed only in the curved trend vector displaying predicted airplane position 30, 60, and 90 seconds ahead. The pilots used the EHSI as the primary display for initiating and during most of the turn onto the final straight segment. The pilot could readily determine the initiation point for the turn and then attempted to position the curved trend vector upon the referenced path also presented on the display. The EADI was monitored during this period to assure that the vertical path (3^o descent) was being maintained. The pilot's attention switched to the EADI near the end of the turn as the computer generated runway symbology came into the display's field of view. From this point down to about 15 meters (50 feet) altitude, the pilot used the integrated situation format presented on the EADI as the primary display.

Figure 20 presents the flight-path tracking results of the approaches on the 1.5-nautical mile test path. Although these were the first such approaches made by two pilots, it can be seen that the vertical and lateral tracking are smooth and consistent. An expanded plot of the final portion of the approaches is presented in figure 21. Note that one of the approaches overshoots the referenced path by approximately 100 meters (300 feet). The pilot commented that he had not tracked tightly the lateral path, but that he knew his situation clearly during and at the end of the turn. It can be seen that all the approaches have attained a stable track to the runway by approximately 1.5 kilometers (5,000 feet) from the runway threshold.

Figure 22 presents the vertical and lateral path tracking results for the approaches on the 1.0-nautical mile test path Again, these are the first such approaches flown by the pilots. The lateral tracking data show overshoots of approximately 30.5 meters (100 feet) but the pilots have stabilized the airplane's track to the runway at approximately 0.92 kilometers (3,000 feet) from the runway threshold.

CONCLUDING REMARKS

Three-Nautical Mile Approach Tests

The results of these flight tests show that the addition of perspective runway symbology and relative track information to a baseline EADI format increased flight-path tracking accuracy during the approach to landing t[illegible] under instrument conditions.

Pilot comments indicated that the integrated situation display format brought about a better understanding of the airplane's position and trajectory relative to the runway and runway extended centerline. The integrated display also enabled the pilots to quickly recognize and recover from a close-in, large lateral path deviation with confidence. Limited flight-path performance results using the integrated display compare very favorably with previous fixed-based simulation results. Flight-Director criteria for glideslope and localizer performance for Category II approach conditions were also met with the limited data acquired. The integrated situation format allows the pilot to assess the information and make the corrective flight control inputs, depending on the size of the error and the remaining distance to the runway threshold.

Close-In Approach Tests

The results of the flight evaluation of the 1.5- and 1.0-nautical mile approach tests show good flight-path performance during the turn and on the short-final approach segments. The display information content and format, however, is not considered to be optimized. Further display and control efforts are needed to define the display information requirements for the close-in curved approach-to-landing task.

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2. Steinmetz, G. G.; Morello, S. A.; Knox, C. E.; and Person, L. H., Jr.: Piloted Simulation Evaluation of Two Electronic Display Formats for Approach and Landing. NASA TN D-8183, April 1976.

3. Walsh, T. M.; Morello, S. A.; and Reeder, J. P.: Review of Operational Aspects of Initial Experiments Utilizing the U.S. MLS. Presented at the NASA Aircraft Safety and Operating Problems Conference, Langley Research Center, Hampton, VA, October 18-20, 1976.

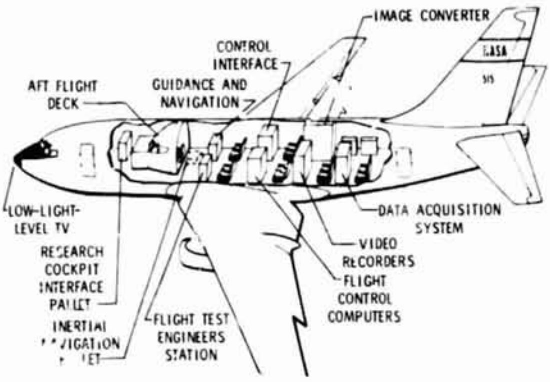

Figure 1.- TCV B-737 internal arrangement.

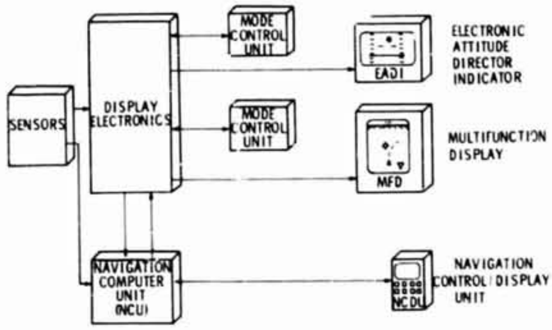

Figure 4.- Navigation, guidance, and display system block diagram.

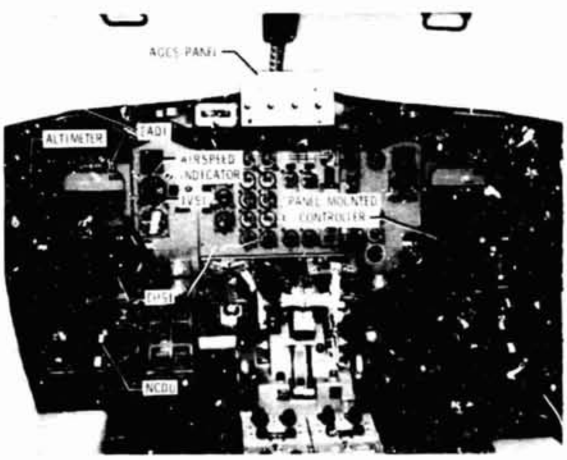

Figure 2.- AFD cockpit control and display layout.

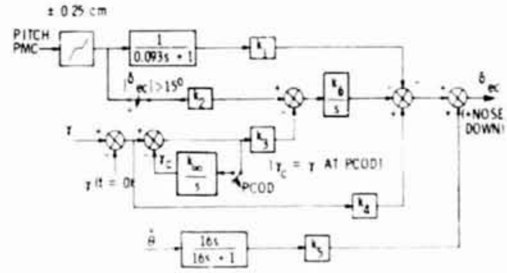

Figure 5.- Velocity vector control mode for pitch axis.

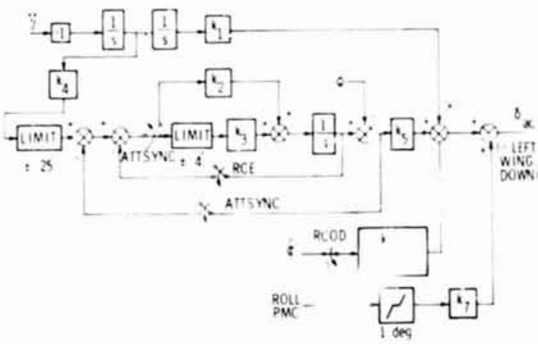

Figure 6.- Velocity vector control mode for roll axis.

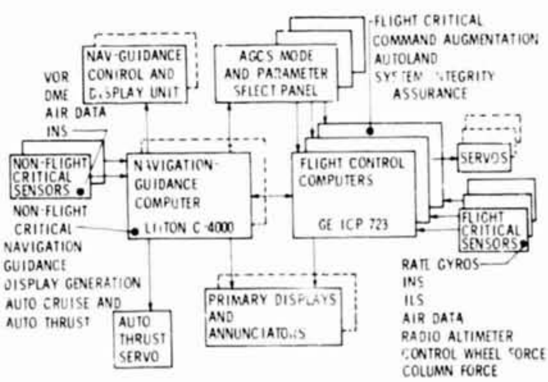

Figure 3.- Advanced guidance and control system (AGCS) concept.

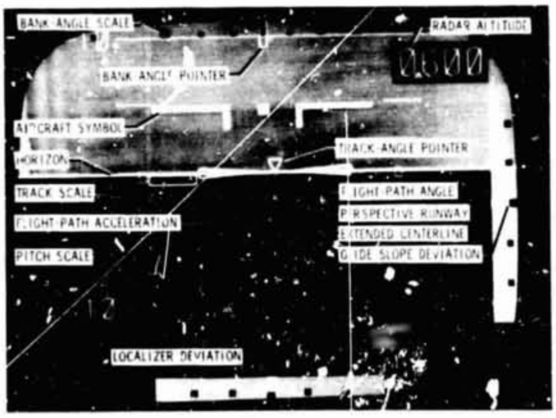

Figure 7.- EADI display information.

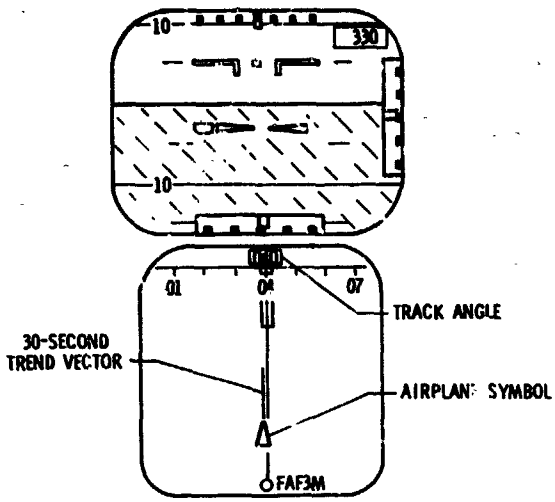

Figure 8.- Baseline situation display format.

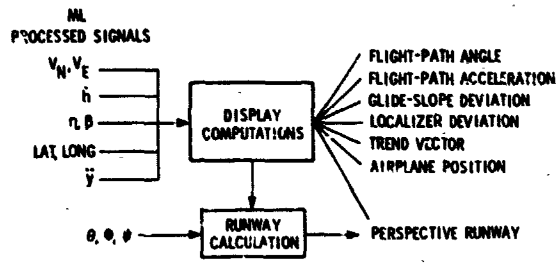

Figure 11.- MLS processed signals used for display information.

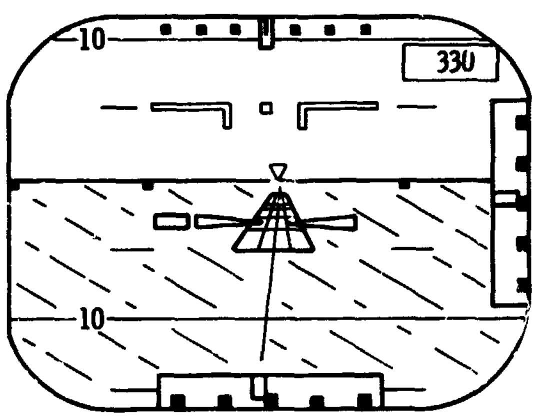

Figure 9.- Integrated display format.

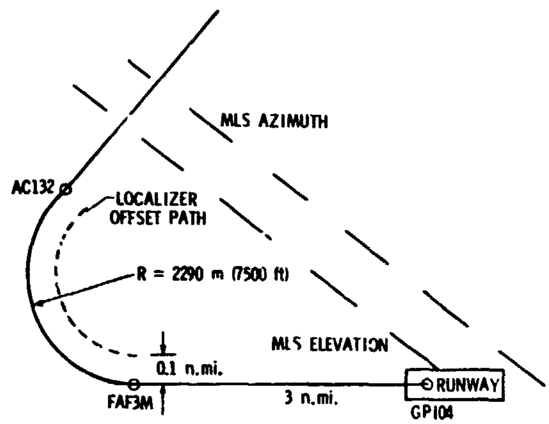

Figure 12.- Plan view of approach path to runway 04 at the NAFEC.

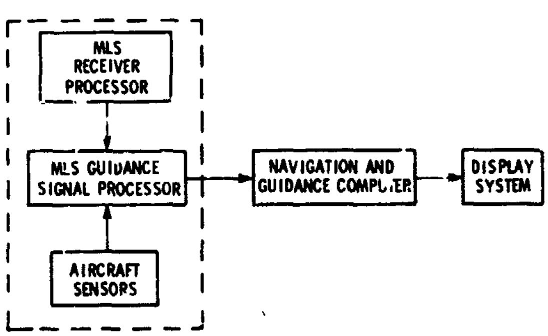

Figure 10.- MLS signal integration with navigation, guidance and display systems.

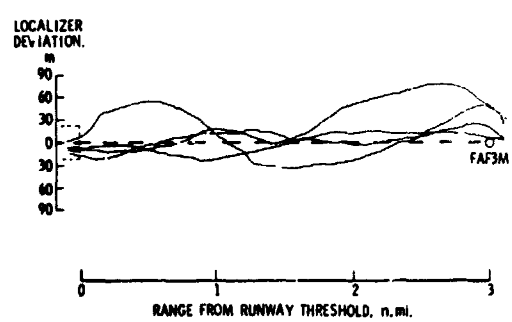

Figure 13.- Localizer tracking performance using the baseline situation display format.

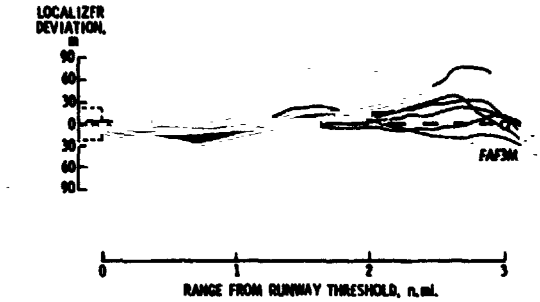

Figure 14.- Localizer tracking performance using the integrated situation display format.

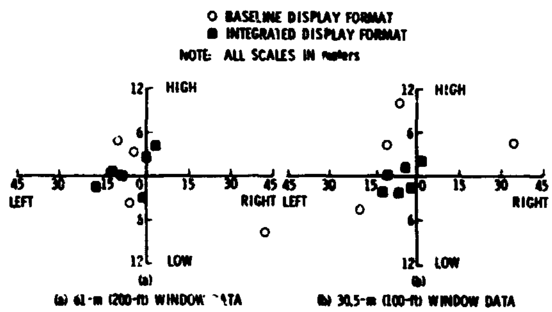

Figure 15.- Window data of glideslope and localizer deviations.

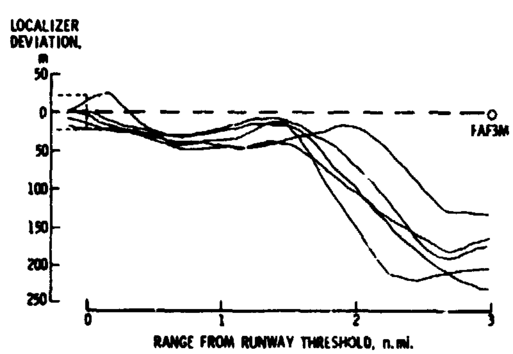

Figure 16.- Localizer tracking using the baseline display format.

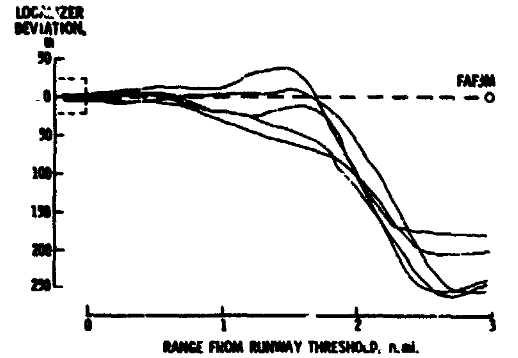

Figure 17.- Localizer tracking using the integrated situation display format.

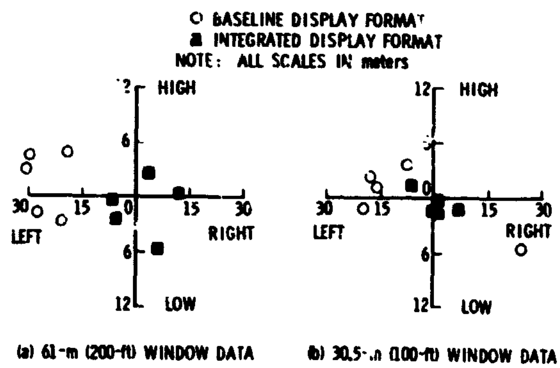

Figure 18.- Window data of glideslope and localizer deviations.

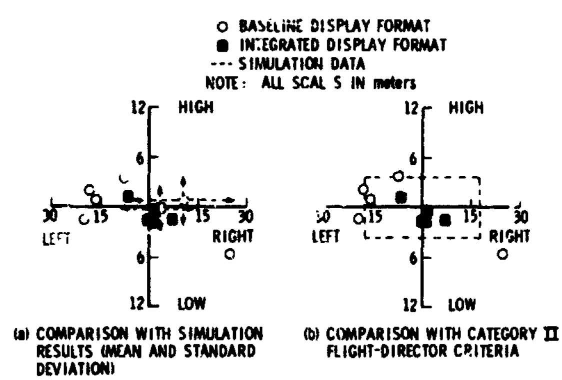

Figure 19.- Flight-path performance comparisons at the 30.5-m (100 ft) window.

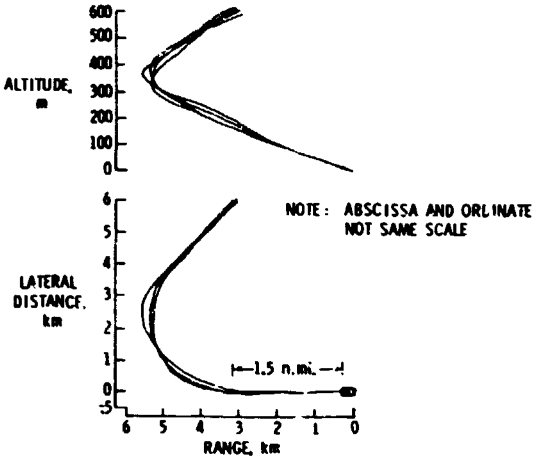

Figure 20.- Manual tracking on 2.78 km (1.5 n.mi.) approach path.

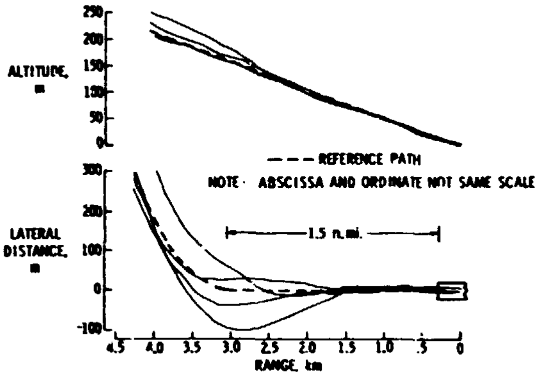

Figure 21.- Manual tracking results on 2.78 km (1.5 n.mi.) approach path.

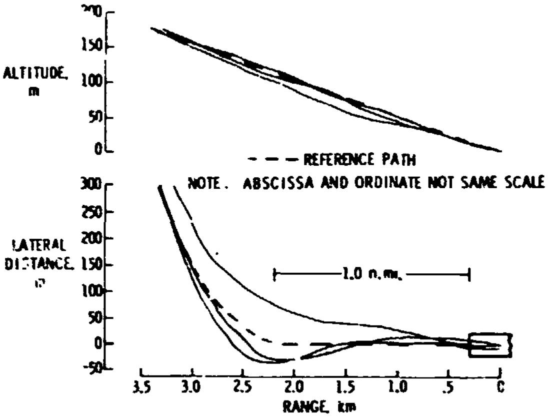

Figure 22.- Manual tracking on 1.85 km (1.0 n.mi.) approach path.